Comparison of Pipe Models to Simulate *Legionella* Concentration in Domestic Hot Water

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Abstract

The production of Domestic Hot Water (DHW) dominates the total energy demand in well-insulated and airtight buildings because DHW is produced above 55-60°C to kill *Legionella pneumophila*. This temperature has a negative effect on the efficiency of DHW production units.

A simulation model is developed that allows to investigate the infection risk for *Legionella pneumophila* in the design phase of a DHW system and to test the effectiveness of thermal disinfection. Different existing Modelica pipe models are investigated to select useful models that can be extended with equations for simulation of bacterial growth in DHW. When implementing the adapted pipe model in a DHW recirculation system, simulation results show that energy use can be reduced by 34% without increasing infection risk.

By developing a simulation model, HVAC designers will be able to assess the infection risk associated with their design and to optimize temperature regimes to reduce the energy demand for DHW production.

Introduction

State of the art

With ever-improving insulation levels and air tightness of building envelopes due to the tightening of energy performance requirements for buildings, the production of DHW, which has seen comparatively little innovation, now dominates the total energy demand of well-isolated and airtight buildings. On average, about 800kWh per occupant per year is needed for DHW production. For the average dwelling with a floor area of 170m² and 3.5 occupants (Defruyt et al., 2013), this amounts to 15kWh/m² a year (blue bar on *Figure 1*). This demand is unchanged, while projected energy performance requirements for 2020 state to reduce the total energy demand for heating, cooling and DHW production to 1/3 of what they were in 2006.

Problem statement

One of the main reasons for the high energy demand is that DHW is produced, stored and distributed at temperatures above 55-60°C to mitigate the risk of infecting the DHW system with *Legionella pneumophila*, a bacteria which causes, upon exposure, acute respiratory disease or severe pneumonia. At these temperatures, *Legionella pneumophila* growth is stopped and remaining bacteria are effectively killed. For most of the DHW applications, like taking a shower or washing hands, temperatures of only 30-40°C are required. This disparity (between 55-60 and 40°C) doubles the temperature difference between DHW system and environment (around 20°C) and has a detrimental effect on the efficiency of DHW production units such as heat pumps.

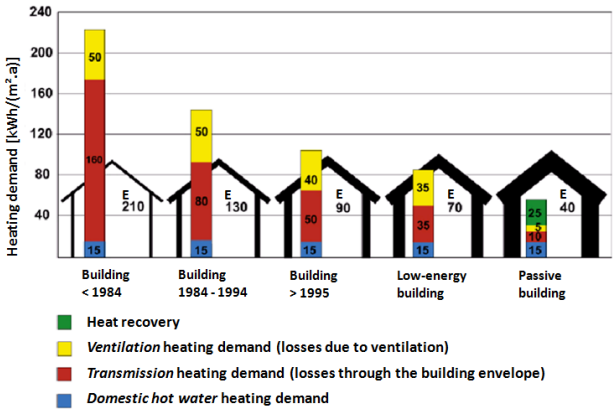

Figure 1: Heating demand of buildings with different building envelope isolation and air tightness levels.

Simulation and experiment

Methods

A simulation model is developed that allows to investigate the infection risk for *Legionella pneumophila* in the design phase of a DHW system and to test the effectiveness of thermal disinfection on an infected system while keeping an equilibrium between energy efficient and healthy buildings. The simulation model will be validated in future research based on test rig and case study measurements.

Background simulation model

In literature, there are no previous efforts to model the dependencies between *Legionella* growth and energy efficiency because of the multidisciplinary topic, so this is the first approach to make a simulation model.

The biological growth model is made up of a number of sub-equations:

1. water based proliferation of the bacteria (growth and transport in water),
2. biofilm growth,
3. *Legionella pneumophila* growth in biofilm and
4. bacteria transport between biofilm and water.

To model the proliferation of *Legionella pneumophila* in water, it is modelled as a pollutant with a variable source term in different DHW components, for example pipes (topic of this paper). Based on an extensive literature review, the main parameters that have an impact on the growth of the bacteria are selected and added to the model as equations. This includes the equations of water temperature and flow conditions.

Multiplication of *Legionella* is mainly dependent on water temperature and flow rate, followed by nutrient availability. At temperatures below 20°C, the bacteria become dormant but remain viable for months. The bacteria grow best at temperatures between 20°C and 45°C with an optimum at 35°C. Beyond 45°C, pasteurization starts and higher temperatures will eventually kill the organism. The death rate at any temperature is proportional to the number of living cells present (Brundrett, 1992) (*Equation 1*).

$$\text{Death rate: } dn/dt = B \cdot n \qquad (1)$$

$$\text{Number of cells: } n = n_0 \cdot e^{-B \cdot t}$$

Where n is the number of cells present at time t, t is the time, B is a constant which is a function of the water temperature, the species of the organism and the chemical nature of the water and n_0 is the number of cells at time t = 0.

Hydraulic model: water vs biofilm

Legionella pneumophila species appear in water and in biofilm (*Figure 2*). This biofilm structure is composed of a consortium of microbial cells that are attached to the surface and associated together in a matrix. Modelling of the biofilm is important because 95% of *Legionella* are surface-associated (Flemming, 2002). Furthermore, *Legionella* bacteria present in biofilm are protected against environmental factors and water disinfection treatments (Cervero-Aragó, 2015). Research reported a better resistance of *Legionella pneumophila* to higher temperatures when present in biofilm. Therefore, the association established between *Legionella pneumophila* and amoebae in biofilms in DHW systems indicate an increased health risk.

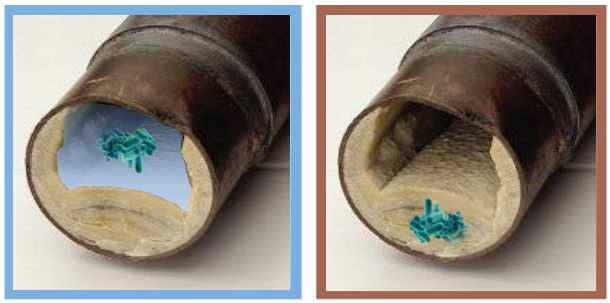

Figure 2: Legionella in water (left) and Legionella in biofilm (right) growth.

Figure 3 shows the temperature dependent growth function of *Legionella pneumophila* bacteria in water and in biofilm.

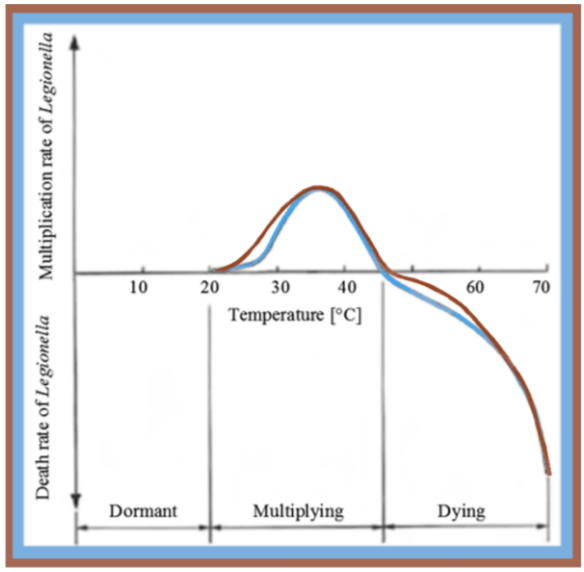

Figure 3: Growth function of Legionella pneumophila in water (blue) (Brundrett, 1992) and in biofilm (brown).

Adapting an existing pipe model

Figure 4 shows the modelling approach for *Legionella* concentrations in pipe models.

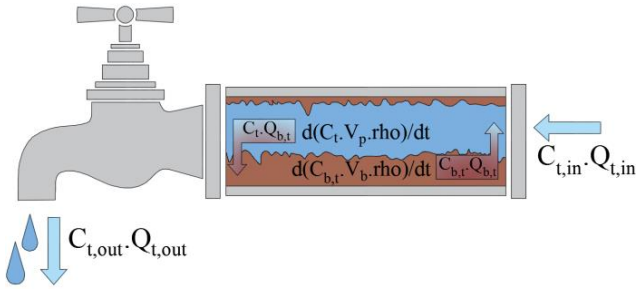

Figure 4: Concentration of Legionella pneumophila in DHW pipe.

To model *Legionella* growth in a pipe, equations need to be added to the hydraulic model. Following mass balance equation, which predicts *Legionella pneumophila* growth, needs to be coupled to an existing pipe component (*Equation 2* and *3*).

$$\frac{C_t \cdot V_p \cdot \rho - C_{t-1} \cdot V_p \cdot \rho}{t-(t-1)} = C_{t,in} \cdot A_{in} \cdot \vec{v}_{t,in} \cdot \rho - C_{t,out} \cdot A_{out} \cdot \vec{v}_{t,out} \cdot \rho + Sources - Sinks \quad (2)$$

$$\Leftrightarrow \frac{d(C \cdot 1000 \cdot V_p \cdot \rho)}{dt} = C_{t,in} \cdot Q_{t,in} - C_{t,out} \cdot Q_{t,out} + \frac{d(C_t \cdot 1000 \cdot V_p \cdot \rho)}{dt} + C_{b,t} \cdot Q_{b,t} - C_t \cdot Q_{b,t}$$

With:

$$Q_{t,in} = Q_{t,out} \quad (3)$$

$$\frac{dC_t}{dt} = C_0 \cdot \frac{ln(2)}{y1} \cdot e^{\frac{ln(2)}{y1} \cdot t} \textit{(growth)} \quad (4)$$

or

$$\frac{dC_t}{dt} = C_0 \cdot \frac{ln(1/10)}{y2} \cdot e^{\frac{ln(1/10)}{y2} \cdot t} \textit{(starvation)} \quad (5)$$

y_1 in *Equation 4* and y_2 in *Equation 5* are temperature dependent. y_1 is the mean generation time (time to double the number of cells). y_2 is the decimal reduction time (time to reduce *Legionella* with 90%, 10% remains). y_1 is the mathematical translation of *Figure 5* and y_2 of *Figure 6*.

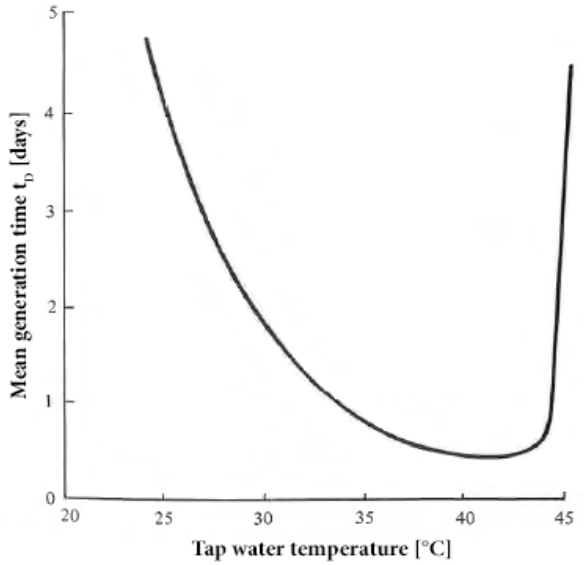

Figure 5: An estimation of mean generation time (time to double the number of cells) of Legionella pneumophila in tap water (Yee and Wadowsky, 1982; Brundrett, 1992).

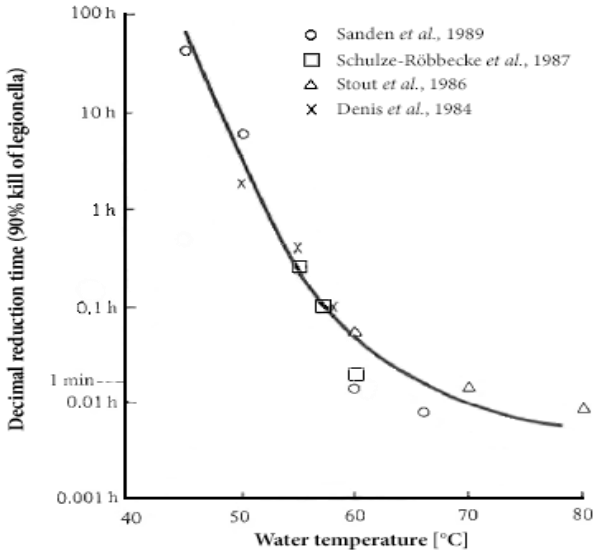

Figure 6: The change in decimal reduction time (90% reduction in Legionella pneumophila) with temperature. (Data from Dennis et al., 1984; data from Stout et al., 1986; Brundrett, 1992).

At certain critical temperatures there is an endless increase of *Legionella* concentration in simulation where in reality after a while a stabilization in concentration will be noticed. This occurs because the system can only hold as many *Legionella* bacteria as nutrients can support. To take nutrients into account parameter *K* is added to the mass balance equations. Population growth under the Verhulst-Pearl logistic equation is sigmoidal (S-shaped), reaching an upper limit at carrying capacity *K*. *K* is the maximum concentration of *Legionella pneumophila* that food can support (*Equation 6*). Populations initiated at densities above *K* decline exponentially until they reach *K*, which represents the only stable equilibrium (Panikov, 1995).

$$\frac{dC}{dt} = B \cdot C_t \cdot \left(\frac{K - C_t}{K}\right) \quad (6)$$

To find the most suitable pipe component for this simulation purpose a comparable study is performed. First of all a suitable simulation environment and libraries are chosen. Subsequently an adequate pipe component is chosen.

Simulation environment

To compile the simulation model, the Modelica environment is used (Modelica, 2016). This equation based programming language is non-proprietary and object oriented, making it appropriate for the development of multi-scale (thermodynamic and biologic) models such as required here.

The work within this project will add to the capabilities of the Modelica simulation environment by providing a biological growth library that is not available today. Modelica's open source and modular structure will allow users to use this library to model similar biological growth problems in all kinds of applications. This approach is preferred over creating a multi-simulation environment from available part-models. The goal is to have a tool that

is flexible and that can be used in multiple contexts, from design to decontamination. Having a large number of different tools work together in such conditions is much less stable. Additionally, it requires that the users are acquainted with all different simulation packages and is less flexible towards extensions of the model to other situations.

Extensive libraries for the simulation of buildings and their services have been developed in IEA EBC Annex 60. The Annex 60 integrated core libraries are compatible with other Modelica building energy simulation libraries. For this study existing models of the integrated Buildings, OpenIDEAS and standard Modelica library are compared because all three libraries contain building as well as system components for energy performance simulation.

Comparison of pipe models

A DHW system is composed of different components, for example heat exchangers, storage tanks, expansion vessels,…, but the main part of the system consists of piping. Different existing pipe models (*Figure 7*) are investigated to select useful models that can be extended with equations for simulation of bacterial growth in DHW. Other DHW components are part of future research, but the modelling approach is similar.

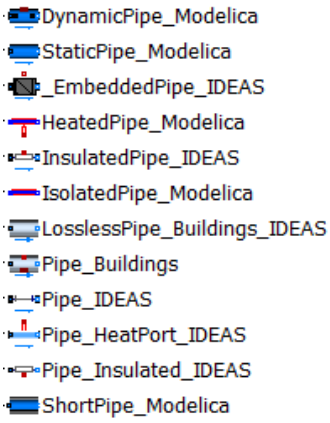

Figure 7: Investigated existing pipe models in Modelica.

The benefit of modelling *Legionella* growth into the pipe model is the ease of compiling simulation models of different systems later on by dragging and dropping the different DHW components (including bacteria growth equations) into the system model.

All pipe models were compared based on a number of parameters necessary for modelling bacteria growth, which may or may not be taken into account in the existing models. The parameters are divided into three categories, mass balance (*Equation 7*), momentum balance (*Equation 8)* and energy balance equations (*Equation 9*).

Each simulation component exists of (parts) of these three physical laws. Conservation of mass is modelled with a differential continuity equation and momentum balance (Newton's second law of motion) with Navier-Stokes equation for incompressible flow.

1. Mass balance: $\frac{\partial \rho}{\partial t} + \nabla \cdot \rho v = 0$ (7)
   - Trace substances → $\frac{\partial \rho}{\partial t}$

2. Momentum balance: $\rho \frac{Dv}{Dt} = \rho g - \nabla P + \mu \nabla^2 v$ (8)
   - Gravity → ρg
   - Pressure drop → ∇P
   - Laminar/turbulent flow → ∇P or $\mu \nabla^2 v$
   - Friction → $\mu \nabla^2 v$ or Φ
   - Material roughness → $\mu \nabla^2 v$ or Φ

3. Energy balance: $\nabla \cdot k \nabla T + \dot{q} + \Phi = \rho c_v \frac{DT}{Dt}$ (9)
   - Heat source → $\dot{q}$
   - Heat exchange → $\nabla \cdot k \nabla T$
   - Insulation → $\nabla \cdot k \nabla T$
   - nNodes → $\nabla \cdot k \nabla T$

The mass balance parameter 'trace substances' indicates if the existing pipe component contains certain equations to add substances to water.

Momentum balance parameter 'gravity' defines if the pipe can be used in all directions (vertical/horizontal). A pipe model without inclusion of gravity can only be used horizontally. 'Pressure drop' inclusion is important because it influences the fluid flow, which in return influences the growth of *Legionella* bacteria. The momentum balance parameter 'state of the flow (laminar/turbulent)' is a meaningful parameter for the purpose of this research because *Legionella* growth is flow dependent. Momentum balance parameters like 'friction' and 'material roughness' are significant parameters in a pipe component to model the growth of *Legionella* bacteria because these parameters influence the amount of biofilm formation.

Energy balance parameters, for example the possibility to add a 'heat source' and 'insulation' are meaningful parameters to take into account, it assures the pipe can be used in as many system configurations as possible. 'nNodes' means that the pipe can be divided into a predefined number of volume segments. 'Heat exchange' is the exchange of heat with the environment, which is an important part of the model to match real conditions because this influences the water temperature a lot, and this in turn affects the growth or starvation of *Legionella* bacteria.

Table 1 gives an overview of all selected existing pipe models with their parameters. If the parameter is indicated by '1' (green) it is taken into account, if it is indicated by '0' (red), the parameter is not part of the existing model. When the value is between brackets, it is an estimation that needs further investigation.

Table 1: Comparison of DHW pipe models

Data			Mass balance	Momentum balance					Energy balance			
Name	**Library**	**Description**	**Trace substances**	**Gravity**	**Pressure drop**	**Laminar/ turbulent flow**	**Friction**	**Material roughness**	**Heat source**	**Heat exchange**	**Insulation**	**nNodes**
Dynamic pipe 	Modelica 3.2.1	Dynamic pipe model with storage of mass and energy	1	1	1	1	1	1	0	1	0	1
Static pipe 	Modelica 3.2.1	Basic pipe flow model without storage of mass or energy	0	1	(1)	0	1	1	0	0	0	0
Heated pipe 	Modelica 3.2.1	Pipe with heat exchange	0	(1)	1	1	1	0	1	1	0	0
Isolated pipe	Modelica 3.2.1	Pipe without heat exchange	0	(1)	1	0 (only laminar)	1	0	0	0	0	0
Short pipe 	Modelica 3.2.1	Simple pressure loss in pipe	0	0	1	0	1	0	0	0	0	0
Embedded Pipe 	OpenIDEAS 0.3.0	Embedded pipe model based on prEN 15377 and (Koschenz, 2000)	1	0	1	1	1	1	0	1	1	0
Insulated pipe 	OpenIDEAS 0.3.0	Insulated pipe characterized by a UA value	1	0	1	1	1	0	0	1	1	0
Pipe 	OpenIDEAS 0.3.0	Pipe without heat exchange or pressure drop	1	0	0	0	0	0	0	0	0	0
Pipe heatport 	OpenIDEAS 0.3.0	Pipe with HeatPort	1	0	1	1	1	0	0	1	0	0
Pipe insulated 	OpenIDEAS 0.3.0	Pipe with insulation, characterised by UA	1	0	1	1	1	0	0	1	1	0
Lossless pipe 	OpenIDEAS/ Buildings 3.0.0	Pipe with no flow friction and no heat transfer	0	0	0	0	0	0	0	0	0	0
Pipe 	Buildings 3.0.0	Pipe with finite volume discretization along flow path	1	0	1	1	0	1	0	1 (multiple heat ports)	1	1

Out of the comparison of the different pipe models in *Table 1*, the models suitable for the authors' applications are chosen. Four models are suitability for this application (*Table 2*).

Table 2: Suitable DHW pipe models

Pipe model	Library	Description
Dynamic pipe	Modelica 3.2.1	Dynamic pipe model with storage of mass and energy
Insulated pipe	OpenIDEAS 0.3.0	Insulated pipe characterized by a UA value
Pipe Insulated	OpenIDEAS 0.3.0	Pipe with insulation, characterized by UA
Pipe	Buildings 3.0.0	Pipe with finite volume discretization along flow path

Of these four models, the most suitable one is adapted to yield the results shown. 'Dynamic pipe' model was not chosen for further development because insulation of the pipe has not been taken into account in the standard model. 'Insulated pipe' and 'Pipe Insulated', two very similar models, cannot be divided into smaller pipe segments (nNodes). Moreover, material roughness, a parameter that is important to simulate biofilm formation, cannot be taken into account. That is why these models were not retained. The authors choose to adapt the 'Pipe' model from the Buildings (3.0.0) library. Gravity equations are missing from this Pipe component, these had to be added in a similar way as the Height(port_b) - Height(port_a) equation in the Dynamic pipe model.

Discussion and result analysis

An example of modification of the retained Pipe model from the Buildings (3.0.0) library can be seen in *Figure 8*. The brown rectangles represent visually the addition of biofilm and the black circles the exchange of bacteria between biofilm and water.

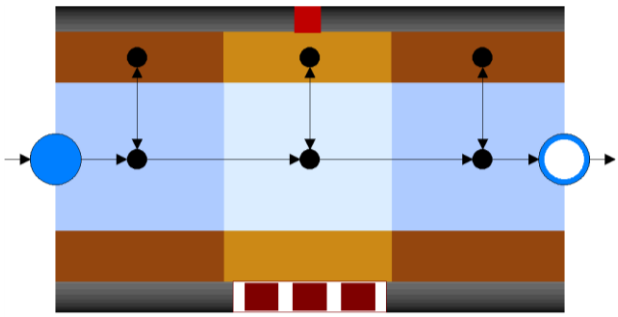

Figure 8: Addition of Legionella pneumophila growth equations to existing pipe model.

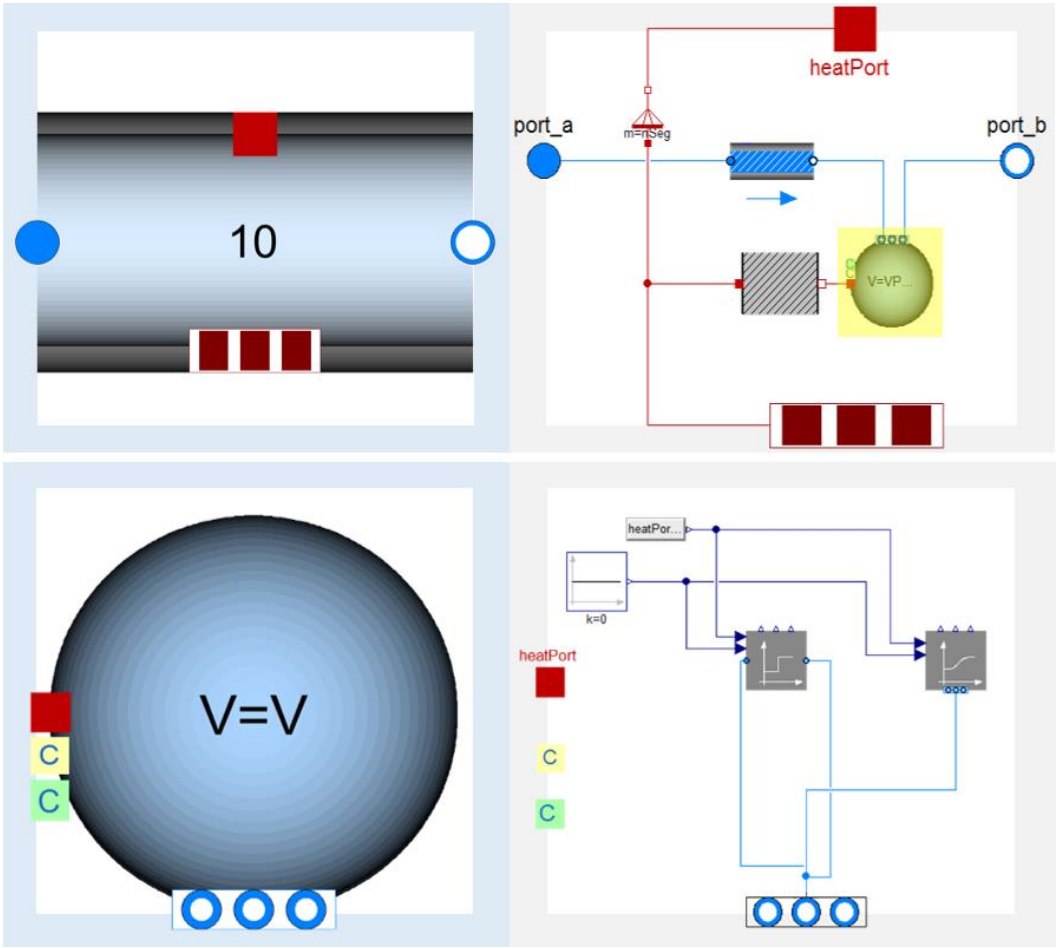

Figure 9: Pipe model in Buildings (3.0.0) library with addition of Legionella pneumophila growth equations in mixing volume (highlighted in yellow).

While *Figure 8* shows the visual additions, *Figure 9* shows the thermodynamic and biologic adaptation of the retained Pipe model from the Buildings (3.0.0) library. All fluid containing components in the Buildings (3.0.0) library consist of a mixing volume; this is the fluid volume that in this application contains water. The mixing volume has a HeatPort, the same logic has been followed to add certain concentrations to the fluid in the pipe. A port to add a concentration of *Legionella pneumophila* (yellow C) and a port to add a concentration of nutrients (green C) is added to the mixing volume. On top of *Figure 9* the icon (left) and diagram view (right) of Pipe model are shown. The mixing volume is highlighted in yellow in the diagram view. At the bottom of *Figure 9*, the icon (left) and diagram view (right) of the mixing volume is shown with addition of the two concentration ports below the red HeatPort.

Domestic hot water system model

The Buildings (3.0.0) Pipe model, with addition of *Legionella pneumophila* growth equations in water and biofilm, can now be used to build different DHW system configurations. The most important collective distribution systems are recirculation systems (*Figure 10*), radial systems (*Figure 11*) and tree systems (*Figure 12*).

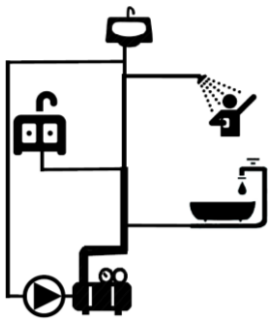

Figure 10: DHW recirculation distribution system.

Figure 11: DHW radial distribution system.

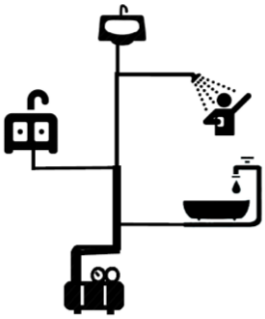

Figure 12: DHW tree distribution system.

Because recirculation systems are the most critical ones in case of *Legionella* infections, the case study building which is modelled here is chosen to be an apartment building with 134 apartments and recirculation distribution system (*Figure 13*).

The questions which need to be answered with simulations are:

- "Can we lower the DHW energy demand by reducing temperature?"
- "How much can we lower the production temperature without compromising on comfort requirements while keeping *Legionella* infection risk as low as possible?"
- "Can we give a thermal shock of X°C every Y days during Z minutes and what are the X, Y and Z values for every case study DHW system?"

The requirement is a *Legionella* concentration of less than 1000 cfu/l (colony forming units a liter), this requirement is giving as a boundary condition to the model and determines the interval of the shock desinfection (Y days). The X, Y and Z parameters are unknowns which will be different for every case study building. A simulation is necessary to determine these parameters for a specific case.

When implementing the adapted pipe model in the DHW recirculation system of this case study building, simulation results show that it is possible to lower the DHW production temperature from 61-64°C (current used temperature regime) to 49-51°C, while adding shock disinfection every 12 days at 70°C for 3 minutes. This measure does not increase infection risk and reduces energy use by 34%.

According to the simulations this measure decreases the total primary energy consumption for DHW from 238 000 kWh/year to 157 254 kWh/year. The primary energy consumption for DHW is defined as the total energy consumption for the production of DHW times the conventional conversion factor to primary energy of the energy using device (for example: times 2.5 for electricity use) (EPB, 2017).

Because it is interesting to see how the inclusion of the *Legionella* model in the pipe elements affects the numerical efficiency of the Modelica models, the system model is run once without *Legionella* model and once with *Legionella* model. The integration algorithm used is Lsodar (tolerance 0.0001). The CPU time for integration is increased with 30% for the adapted model.

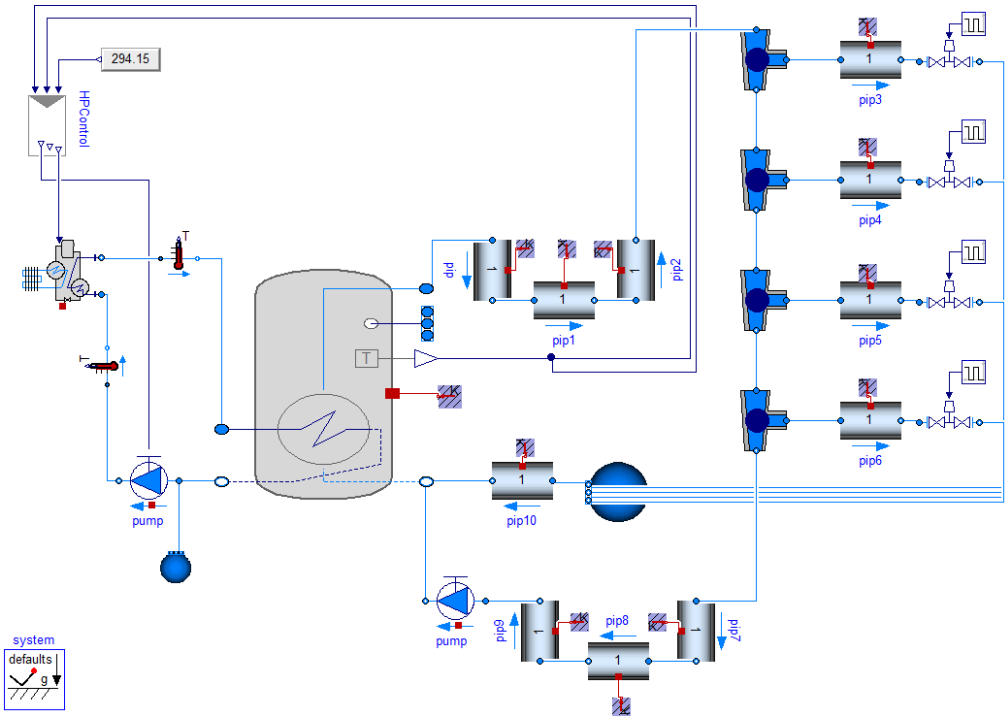

Figure 13: DHW system of an apartment building with recirculation distribution system.

Validation - test rig

Validation of the simulation model is part of future research, but an outline is given on how this will be done.

Eradication of *Legionella* is a critical issue, to transpose the results of the simulation studies into practice, the model needs to be validated first. That is why in addition to the modelling work, a test rig is built.

The test rig is part of the 'Instal2020' project and is constructed in collaboration with the Belgian Building Research Institute (BBRI/WTCB/CSTC) in their accredited laboratory. The test rig serves to run experiments that allow testing, validating and improving the simulation model, to see if all relevant parameters for the prediction of *Legionella* growth and removal are accurately predicted and to test the assumptions that are made to close the gaps in available knowledge. Therefore, the test rig meets following specifications:

- is composed of realistic elements of DHW systems,
- have flexibility to test different system configurations,
- allow to apply dynamic use patterns (kitchen and shower profile),
- allow to monitor water velocity and temperature at the inlet and outlet of each specific section of the DHW system,
- have a number of *Legionella* sampling points that allow to take samples without being exposed to contaminated water,
- allow easy disassembly for decontamination,
- have a large contaminated water storage (left boiler).

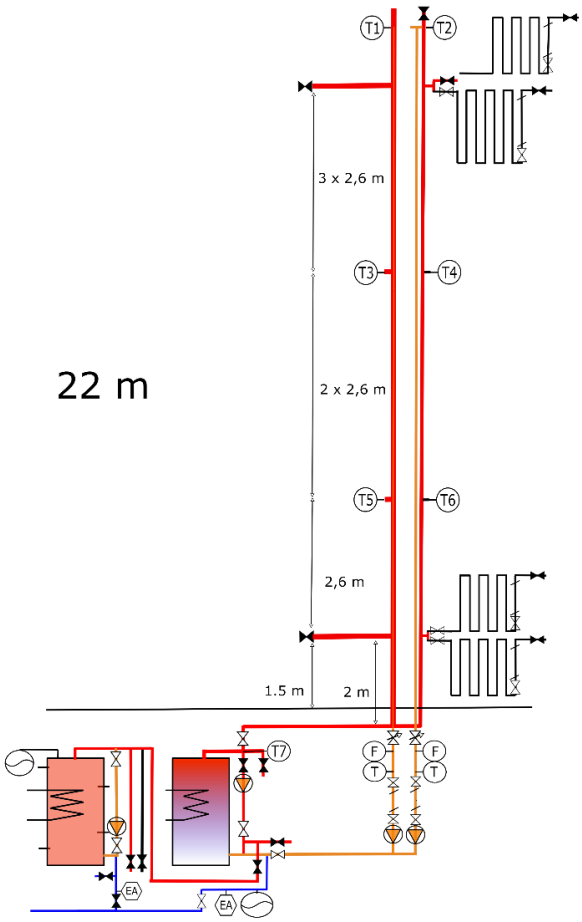

Figure 14: Configuration of the test rig with in red supply and in orange retour pipes. There are two systems: a pipe-in-pipe system on the left and a recirculation system on the right (WTCB).

The test rig is 22 meter high and consists of two hot water distribution system configurations that are contaminated with *Legionella pneumophila* (*Figure 14*). The test rig is up and running and tests started in January 2017. For each configuration, an 'as is' test will be followed by a set of two additional tests, the first with altered temperatures for low energy use, the second running a decontamination procedure on the infected system. This test rig allows model validation under different operating conditions.

Validation - case study buildings

Test rig conditions are sometimes slightly different from in situ conditions, that is why a second validation will be performed in future research based on measurements in case study buildings (*Figure 15*). In the case study buildings, different systems for DHW production and distribution are implemented. Temperature profiles, flow conditions and DHW use are monitored on several locations within the installation. Simulation model validation is possible for temperature, flow condition and *Legionella pneumophila* growth parameters.

Figure 15: Case study buildings.

Conclusion

By comparing pipe models, it is possible to select the best one to model *Legionella* concentration in DHW. By developing a simulation model that allows assessing the infection risk for *Legionella pneumophila* in the design phase of a DHW system under dynamic conditions, HVAC designers will be able firstly to thoroughly assess the infection risk associated with their design and secondly to optimize the temperature regimes, choose better hydronic controls and reduce the energy demand for DHW production.

Acknowledgement

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Nomenclature

- $C_{t,in}$ *[cfu/l]* Concentration of *Legionella pneum.* in water entering the system
- $C_{t,out}$ *[cfu/l]* Concentration of *Legionella pneum.* in water leaving the tap
- C_t *[cfu/l]* Concentration of *Legionella pneum.* in water at time t
- $C_{b,t}$ *[cfu/l]* Concentration of *Legionella pneum.* in biofilm at time t
- $Q_{t,in}$ *[kg/s]* Mass flow rate of *Legionella pneum.* in water entering the system
- $Q_{t,out}$ *[kg/s]* Mass flow rate of *Legionella pneum.* in water leaving the tap
- $Q_{b,t}$ *[kg/s]* Mass flow rate of *Legionella pneum.* entering/leaving the biofilm
- V_p *[m³]* Volume of water in pipe
- V_b *[m³]* Volume of biofilm in pipe
- dC/dt Changing concentration of *Legionella pneum.* over time
- C_0 *[cfu/l]* Start concentration of *Legionella pneum.* in water entering the system
- t *[s]* Time
- K *[cfu/l]* Carrying capacity
- p *[kg/m³]* Mass density of mixture
- v *[m/s]* Mass-average velocity for multicomponent mixture
- D *[m]* Tube diameter
- g *[m/s²]* Acceleration due to gravity
- P *[Pa]* Total pressure
- μ *[Pa·s]* Viscosity
- k *[W/m·K]* Thermal conductivity
- T *[K]* Absolute temperature
- $\dot{q}$ *[W/m³]* Volumetric energy generation rate
- Φ Function of fluid viscosity and shear strain rates
- c_v *[J/kg·K]* Heat capacity

References

Brundrett, G. (1992). Legionella and Building Services, 46.

Cervero-Aragó, S., Rodríguez-Martínez, S. et al. (2015) Effect of common drinking water disinfectants, chlorine and heat, on free Legionella and amoebae-associated Legionella. PLoS ONE, 10(8).

Defruyt, T., Delghust, M., Laverge, J. et al. (2013). Evolution of Energy Performance of Houses and the Interaction with Energy Performance Regulation. Article in proceedings. In: Proceedings of Clima, Prague, Czech Republic, June 16-19.

EPB (2017). Appendix V, 118. Available: http://www.energiesparen.be/epb/bijlagen.

Flemming, H.C., Walker, J.T. (2002) Contamination potential of biofilms in water distribution systems. Water Science and Technology: Water Supply, 2(1), 271-280.

Modelica (2016). Available: http://www.modelica.org.

Panikov, N.S. (1995). Microbial Growth Kinetics, Chapman & Hall, London.

Stout, J.E., Best, M.G., Yu, V.L. (1986). Susceptibility of Members of the Family Legionellaceae to Thermal Stress: Implications for Heat Eradication Methods In Water Distribution Systems. Applied and Environmental Microbiology, 52(2), 396-399.

Yee, R.B., Wadowsky, R.M. (1982). Multiplication of Legionella pneumophila in unsterilized tap water. Journal of Applied Environmental Microbiology, 43, 1330-1334.